Cosmic Chemistry: Cosmogony

Assumptions, Models, and the Scientific Method

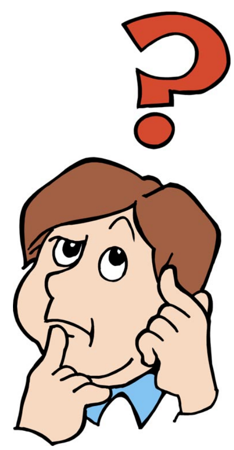
APPENDIX B

Introduction

Much has been written by philosophers, science historians, and scientists about the topics in the title of this appendix. Some of these writings are listed in the bibliography. Here we offer brief summaries of the topics and hope that these tantalizing tidbits will stimulate you to do more in-depth reading and study on your own. We also hasten to add that there are many and varied contemporary opinions about some of the topics. Consequently, do not be surprised if you find yourself in disagreement with some of what is written here. You may find that other writers have different viewpoints from those expressed below.

You also will find that it is sometimes difficult to distinguish among concepts such as **assumptions**, **models**, **hypotheses**, **theories**, and so on. It is particularly difficult to distinguish between assumptions and hypotheses, because a hypothesis is simply a working assumption. More about hypotheses and their place in the scientific method will be found in subsequent sections. There are only a few hard and fast rules that provide the means for making unambiguous decisions about how to label things. So, do not worry about exact definitions at this time. The goal of this text is to stimulate and challenge you to think outside your usual frame of reference. If, after reading what is written here, you have questions and/or doubts, then this text achieved the desired end.

Assumptions



Do you make assumptions in your everyday life? If you are like most people, you do. For example, do you assume that there will be additional earthquakes in California? Do you assume that a mountain lion will not attack you on the way to school? When you were 12 years old, did you assume that someday you would have a driver's license? You probably answered "yes" to all of these questions. You probably do not stop and think about the many subconscious assumptions you make daily.

Do scientists make assumptions or do their experimental results, theories, and laws make it unnecessary to make assumptions? Not at all. Assumptions, or working hypotheses, are a major part of science. In fact, it is difficult to talk for long with a scientist about science without hearing the words, "If we assume." In order to make sense of things, we usually have to make assumptions, which help structure our thinking. Assumptions are important components of the models that we construct to represent atoms, electromagnetic radiation, planetary composition, and so forth. One often makes numerous assumptions at the beginning of an investigation. However, at the end of the investigation, the number of assumptions should be reduced, reflecting the increased level of understanding gained during the research.

An assumption from 19th century involves wave propagation. It was known to early scientists that sound waves require a medium (typically air) for their propagation. Sound is not carried through a vacuum. About 150 years ago it was shown that light consists of waves. It was assumed that light, like other waves such as sound, required a medium for its propagation. This assumption led to the invention of a hypothetical medium for the propagation of light called the "ether." The ether served only one purpose—to be for light what air is for sound. Ultimately it was realized that things that can be done with air (compression, for example), could not be done with the ether. Why? It was because the ether did not exist! The ether had only one property—to make an analogy between the propagation of light and the propagation of sound. Research showed that the initial assumption was incorrect.

Other assumptions from contemporary physics involve the famous statement from Newton that $F = ma$, where F is force, m is mass, and a is acceleration. Beginning physics students learn this equation when they study motion. Is there an assumption here? Don't we assume that there are "things" such as force or lines of force? When we think about an egg being dropped from a building, we may calculate a "force" from Newton's equation, the egg's mass and its acceleration due to gravity. However, the force itself is not measured—there is no such thing as a force meter! We assume that forces exist, but we really do not know what they are. We assume that gravity is always and everywhere attractive. Is this necessarily true?

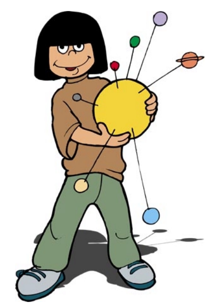
Major assumptions about core concepts of science are made in cosmological research. Dealing with these assumptions is difficult because of our tendency to believe that some of the laws and basic tenets of science are not likely to be violated. That is to say, we live in highly unique (we assume!) surroundings where we enjoy feelings of predictability and knowing. We know the sun will appear to rise in the east in the morning. We can predict with confidence that it will snow somewhere in Colorado during the winter. Our level of certainty about many everyday things provides stability in our lives and confidence about the future. But what about the far reaches of the largely unexplored universe? Do our comfortable ideas still apply there?

Do Newton's laws of motion apply in other parts of the universe? Do the laws of thermodynamics, which are so well established here on earth, apply in those parts of the universe called black holes? Is it possible that other universes exist where the physical laws and principles are totally different from ours? If so, would we be able to recognize that universe?

Cosmologists assume that the physical principles that apply on earth apply equally well to the rest of the universe. Of course, at this point they have no alternatives. It is important that you keep this in mind as you pursue the topics presented in this module.

Models

Children can safely play with models of things that may be too big or too dangerous for them to handle (car, stoves, lawn mowers, babies, etc.). It is sometimes necessary for scientists to "play" with models, too. Frequently, forging new science depends on the development of models. Basically, a model is a scaled-down version of a natural object or system, with details left out. The details that are left out depend on the goals, sophistication, and skill of the scientist doing the modeling. If too much is left out, the model may be almost worthless. If too many details are included, the model may become too complicated to be useful, at least initially.



Upon reflection, it is easy to see why models lack some features of the real system. Often, the objects of a scientist's attention are too small to be observed directly and certain features may be unknown. The system might also be inaccessible for direct visual study for other reasons, such as the center of the Earth or the surface of a distant galactic object. Gravity or magnetism can be studied through their effects on matter. However, neither gravity nor magnetism can be seen directly—they are modeled. You probably can think of other reasons why it's necessary for scientists to develop models as they probe the secrets of nature.

The types of models that scientists develop take many different forms. Sometimes they are actual physical constructions. The Earth, moon, and sun as small wooden spheres that are mechanically moved to illustrate the phases of the moon and eclipses, is one example. Other models may be nothing more than mental images that are developed in an effort to picture something unseen. Picturing the atom as a solar system in which the sun represents the nucleus and orbiting planets represent the electrons is an example of a mental model. Other models are mathematical in nature and depend on algebraic or other kinds of statements to describe a phenomenon or object. Rays of light are good examples, as these can be treated as waves and equations can be developed that describe their properties.

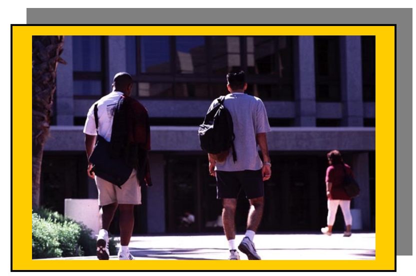
Models usually evolve and improve as scientific advances are made. Sometimes models are thrown out because new evidence proves them misleading or incorrect. Sometimes different models are used to describe the same thing. The choice of models depends on the goal of the scientific investigation or perhaps the scientific sophistication of the individual conducting the work. Once again, a good example is the atom. The solar system model is adequate for many purposes, but a highly mathematical model based on the field of quantum mechanics is necessary for rationalizing other aspects of an atom's behavior. Fundamentally, models are developed in an effort to explain how things in nature work.

The history of cosmology is replete with models of the universe. There is the Big Bang model, the inflationary universe model, and the steady state model. These models necessarily have a strong mathematical flavor, since they usually invoke such esoteric concepts as Einstein's theory of general relativity and related sophisticated ideas from advanced physics.

So, how are models developed? They are developed by making physical observations on a system to establish at least a few facts. Then, by combining these facts with appropriate theories, principles, and assumptions, a “model” that mimics the system is created. It is in this way that science advances, because the models provide a means for making predictions about the behavior of a system. These predictions can be tested later as new theories, measurements, or technologies are brought to bear on the subject. The new measurements may result in modification and refinement of the model, although certain issues may remain unresolved by the model for years. Nevertheless, the goal always is to continue to develop the model in such a way as to move it ever more closely to a true description of a natural phenomenon.

Let’s say that you want to model the motion of your right leg (or your left leg) as you walk. Upon reflection, you might realize that the motion of your leg is somewhat analogous to the motion of a pendulum. Your foot is the bob, your leg is the string connecting the bob to the pivot point, and your hip is the pivot point. Your leg muscles are assumed to play no role in this. Okay, we have made assumptions or, if you wish, stated several hypotheses—this is just a part of scientific investigations. The assumptions are not perfect, obviously, but they provide a good starting point. So if your leg is modeled as a pendulum, is it necessary to describe the exact shape of your foot or can we just let it be represented as a mass? Certainly, the latter approach would be easier. Let’s make that simplification.

What is the mass of your foot? This will require some guesswork, but the mathematical analysis of simple theoretical pendulum motion is independent of the mass of the bob, so the guesswork is not too critical to the success of the model. What is the length, (L) of the pendulum? Well, that can be determined experimentally to a reasonably high degree of accuracy as the distance from your ankle to your hip. As you can see, at this point our developing model involves some assumptions, some guesswork, some approximations, some measurements, and some obvious simplifications. This is the way in which models evolve.



Do you want to include the effect of air resistance on your swinging leg in this model? You probably would want to leave this out, as including it would add unnecessary major complications to the model. To this point, you may crudely describe your leg motion as a simple theoretical pendulum, which was analyzed and modeled mathematically many years ago. The motion is defined by an equation that states that the period (time to perform one complete swing) T is proportional to the square root of the length of the pendulum, L. Finally, it should be noted that something very important has been left out of the model. Do you know what it is? The answer is gravity. Without gravity, the pendulum would not swing back and forth and your leg would hang from your hip (in this model, ignoring muscles, of course) as a more or less useless appendage. But if gravity is included in the equation, the picture is complete, and you have developed a crude mathematical model of leg motion:

$$T=2\bullet\sqrt{L/g}$$

where g is acceleration due to gravity.

While this model is a crude one, you might stop and think about it a bit before dismissing this exercise as just a trite example of model development. Do you think that acceleration due to gravity helps you swing your legs as you walk, sort of like a pendulum? Or do you supply all of your leg motion through sheer muscle power? If you think that gravity does not play a role, see how long you can extend your leg out in front of you by muscle power alone. Do you feel the effect of gravity?

Scientific Method

People use the scientific method daily without realizing it. Think about laundry detergent. Why do you buy a particular brand? It is based on your hypothesis. You have a procedure for washing clothes with built-in variables (size of load, temperature of water, amount of detergent, etc.). You run a series of tests (number of loads of wash) until the detergent is gone. By the time that you have completed your tests (run out of detergent) you have collected enough evidence to determine the effectiveness of the detergent and have probably developed a theory.

As stated earlier, much has been written about the philosophy of science and the scientific method. Presented here are some core ideas to help you extend your knowledge through independent reading.

First, scientists assume that there is a real, structured world in which events are capable of being explained by natural cause and effect principles. It further is generally assumed that humans are capable of understanding the world's structure, but that the existence of the world is independent of human perceptions. Thus, science is guided by the laws of nature and facts must be understood within the context of natural processes. Scientific theories, if they are to be of any use, must be testable against the natural world. The process by which scientists endeavor to construct an accurate representation of the structure of and events in the world is called "the scientific method." This process is designed to eliminate personal and cultural beliefs, as well as other biases, which might influence our perceptions of natural phenomena. Science does not deal with what should be—rather it deals with what is.

Observation

The process of the scientific method involves several steps. The first step of any scientific investigation is observation of a natural phenomenon or group of phenomena. This is a crucial issue in science. Science begins with observations, whether they be observations of motions of the planets from afar, or observations of the effects of mixing chemical A with chemical B in a laboratory test tube. The observations lead to the hard data of science, which are called facts. A fact is defined by the National Academy of Sciences as "an observation about the character of the natural world that has been repeatedly confirmed."

Hypothesis

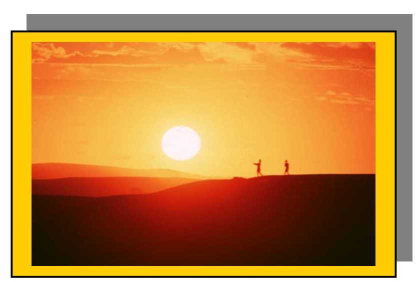
Following the observational, fact-finding phase is the formulation of a hypothesis to explain the phenomenon. The National Academy of Sciences has defined a scientific hypothesis as "a testable statement about the natural world." Often the statement is of a causal relationship among variables that is testable. While a hypothesis is a limited statement that refers to cause and effect in specific situations, it must offer the opportunity for further testing to be very useful. Variables are defined as anything in the natural world that can exist in varying states or levels that are measurable. The length of the day on earth is a good example of a variable.

The next step in applying the scientific method is to use the hypothesis to predict the results of observations or the existence of other phenomena. In a formal sense, the word "model" is used for situations where the hypothesis has at least limited validity. For example, the ideal gas model of the behavior of gases succeeds in mathematically predicting the relationships among pressure, volume, and temperature of gases; however, it fails under close scrutiny, but it does have considerable validity. Once predictions have been made, evidence is collected through experimental tests. Several trials should be completed.

Theory

Now it is necessary to define some of the other words that are often encountered in discussions of the scientific method. The first of these is "theory." This term finds much casual usage in everyday life. You have probably uttered the words "I have a theory about that." We use the term as a substitute for the words "guess," "hunch," and "speculation" in our everyday life. The National Academy of Sciences defines a theory as,"a well-substantiated explanation of some aspect of the natural world that can incorporate facts, laws, inferences, and tested hypotheses." Note the use of the word "explanation." This word distinguishes between a theory and a law.

In a sense, a theory is kind of a catch-all term that represents a hypothesis, or group of hypotheses, that have survived repeated experimental tests. The distinction between a theory and a hypothesis is fuzzy, and the best way to look at it is that a theory is a hypothesis with maturity. When a theory predicts new phenomena that are subsequently observed on a consistent basis, it is considered reliable.



If you see the sun appear to rise, this is an observation that is explained by Newton's very reliable theory of gravity. This theory has been tested time and time again and leads to really accurate predictions. We can imagine that astronauts would be terribly apprehensive about going in orbit around the Earth if they thought that Newton's theory is not reliable. At a more personal level, would you risk stepping off the top of the Empire State Building because you believe gravity does not always apply? Probably not.

Do theories change? Yes, all of the time. They can be crushed by a single fact, although this is rarely the case. They do not represent absolute truth in any sense of the word. They change or fail in the light of evidence collected through experimentation and observation. Consider Newton's theory of gravity. While it works well when applied to large objects, it does not adequately address the behavior of sub-atomic particles. This does not mean that the theory is wrong, it just means that the theory has limited applicability.

A hierarchy of theories exists based on their degree of reliability. Newton's theory of gravitation would be somewhere near the top. The theory that black holes exist might fall somewhere near the middle. The theory that the Earth is flat would fall somewhere near the bottom.

Generalizations and Laws

This brings us to the topic of a scientific law, which is defined by The National Academy of Sciences as, "A generalization that describes how some aspect of the world behaves under stated circumstances." Note that a law describes, whereas a theory explains. Contrary to popular belief, theories do not become laws even when they are consistently supported by experimental evidence. Laws are descriptions of phenomena, but theories are explanations of how and why the world is structured the way it is.

The scientific method is distinguished by its requirement of systematic observations and experimental investigations. It is simple and logical, yet it addresses a very complex issue. How do we come to know what we know? It is important to keep in mind the assumptions that underpin the accumulation of facts and the formulation of explanations for the phenomena in our natural world. The scientific method may be used productively in your everyday life, if you stop and think about it.